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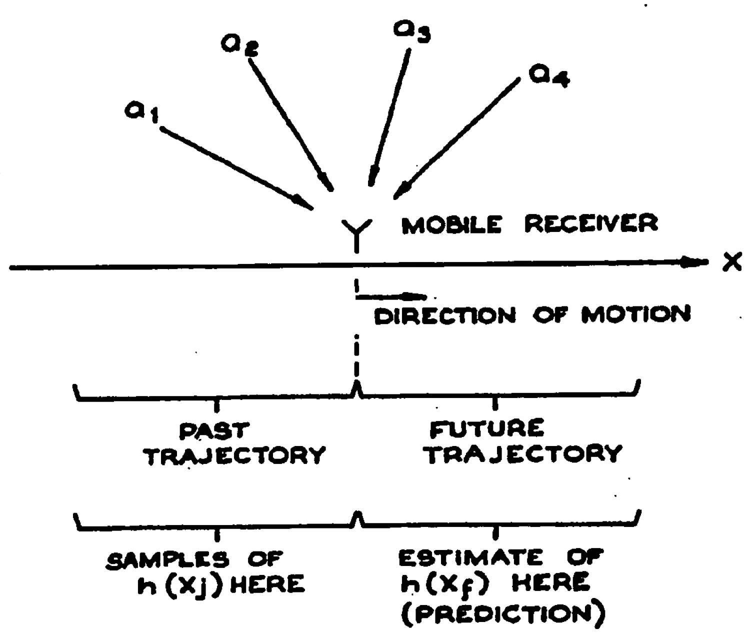
(54) Title: PREDICTION OF SIGNALS IN MOBILE COMMUNICATIONS AND SYSTEMS THAT USE THE PREDICTION FOR SIGNAL RECEPTION AND DECODING

(57) Abstract

A method for predicting the future channel behaviour of a multipath time-varying channel, for example in a mobile communications receiver, comprises obtaining samples of the past channel behaviour from the received signal processing the past samples to characterise the multipath components of the received signal, estimating the future channel behaviour from the estimated multipath signal characteristics (and assuming that the future mobile trajectory is known in the case of a moving receiver), and applying the predicting channel behaviour prediction in the processing of signal subsequently received to improve the channel quality.



PREDICTION OF SIGNALS IN MOBILE COMMUNICATIONS AND SYSTEMS THAT USE THE PREDICTION FOR SIGNAL RECEPTION AND DECODING

FIELD OF INVENTION

The invention comprises a method for predicting future channel behaviour for a multipath time-varying channel, for example in a mobile communications system, and communications systems and receivers.

BACKGROUND OF INVENTION

In mobile communications, and also some point-to-point links, the radio channel imposes a fading signal envelope and randomly changing phase on the received signal. The cause is changing multipath radiowave propagation. The signals borne by the multiple waves from different directions and with different delays are combined in a receiving antenna. The interference between the received signals causing the fading envelope with an associated changing phase. The resultant (received by the antenna) signal has fading which depends on both the frequency of operation and on time.

For the reception and decoding of the information signals carried by the radio waves, the fading and other related distortion caused by the mobile radio channel degrades the quality of the channel, resulting in a degraded spectral efficiency. Signal processing techniques such as equalisation, rake combination, and diversity antennas using signal combination can help mitigate the effects of the multipath-induced degradation. The control of these processes (setting the weights in the equaliser, rake or (other) diversity signal combiner) is adaptive in order to follow the time-varying nature of the channel.

In multi-user systems, capacity is interference-limited. The signal processing solutions for maximising capacity in this case include reception (following the changing phase and amplitude of the interferers) and cancelling the unwanted signals (interferers). The cancellation occurs during controlled combination of

those signals which originate from: different diversity antennas; different time delay bins in the signal from a single antenna; different frequencies from a single antenna; or a combination of these. Here it is both the unwanted signal and interferers that require some degree of reception, in order to implement system capacity-enhancing performance. A central problem in mobile communications is the short-term (several signal fades) unpredictability of the received signals ie, the short-term unpredictability of the mobile channel.

A review of the limitations of mobile communications systems imposed by the "unpredictability" of the channel is in "Estimation of Time-Varying Radio Channels" R.A. Zeigler, J.A. Cioffi, *IEEE Transactions,* Vol VT-41, No.2, pp134-151, May 1992. The basic model for the fading channel (see equation (2) below) is given in texts such as W.C. Jakes, *Microwave Mobile Communications,* AT&T Press, 1974. Reprinted IEEE Press, 1996.

SUMMARY OF INVENTION

In broad terms in one aspect of the invention comprises a method for predicting the future channel behaviour for a multipath time-varying channel, in a communications receiver including an antenna, comprising:

(a) obtaining samples of the past channel behaviour from the signal received by the antenna;

(b) processing the past samples to characterise the multipath components, or an equivalent set thereof, of the signal received by the antenna;

(c) estimating the future channel behaviour from the estimated multipath signal characteristics; and

(d) applying the predicting future channel behaviour in the processing of signal subsequently received to improve the channel quality.

In broad terms in another aspect the invention comprises a communications receiver including an antenna, including:

(a) means arranged to obtain samples of the past channel behaviour from the received signal;

(b) means arranged to process the past samples to characterise the multipath components, or an equivalent set thereof, of the received signal;

(c) means arranged to estimate the future channel behaviour from the estimated multipath signal characteristics; and

(d) means arranged to apply the channel behaviour prediction information in the processing of signal subsequently received to improve the channel quality.

Either the receiving terminal may be mobile or the transmitter may be mobile and the receiving terminal fixed.

Time-dependent fading can be viewed in two ways: the incoming waves are changing in their direction (relative to the receiving antenna), phase and perhaps amplitude; or the receiver is moving relative to the incoming waves. In general, both the incoming waves are changing their characteristics and the terminal is moving relative to them. Often, however, most of the scatterers from which the waves reradiate (including ground and other landscape features, buildings (walls, ceilings), furniture, cars, poles, wires, people, etc) are effectively static. For a static transmitter (eg a fixed base station), the dominant cause of the time variation in the radio channel is the motion of the receiver. For relatively unchanging trajectories of the mobile receiver, typically found in vehicular antenna-based mobile reception, but also in personal (hand-held) terminals for short distances or times, the radio channel can be predicted, if the contributing multipath rays combined in the receiving antenna can be characterised by

estimating the direction, amplitude, and phase of the principal multiple signals received by the antenna.

In the method and system of the invention knowledge of the past behaviour of the received signal (ie samples of the channel) is used to estimate the current channel behaviour (interpolation) and future channel behaviour (excluding extrapolation). In particular, this may be applied to improve existing signal processing techniques (equalisation, rake and diversity combination) to improve the usage of fading channels in mobile and personal communications. "Signal prediction" includes the interpolation of the channel (the channel behaviour at times or positions between the time (or distance) samples of the channel), and extrapolation of the channel at times (or distances) after the last sample of the channel, and also the prediction (and subsequent processing) of interfering channels. This improves the capability of existing signal processing techniques to maximise the wanted signal-to-interfering signal(s) ratio.

"Signal prediction" in the engineering science literature is typically interpreted as using knowledge of current and immediately prior behaviour of a signal - see for example V.A. Golovkov, M.V. Zykin, "Prediction of a random process based on sampling its derivatives", *Radiotekhnika i electronika*, No. 6, pp1049-1053, 1993 and also in *Journal of Communications Technology and Electronics*, Vol 38, No. 6 pp 57-61, 1993. However for a random signal which is truly unpredictable (has no underlying physical process whose interpretation allows prediction), the accuracy of any prediction is limited to less than the correlation time of the signal. The invention relies on the fading channel having an underlying deterministic phenomena, viz., the fact that the channel behaviour is generated from characterised multipath. This allows signal prediction over times much longer than the correlation time of the signal.

DESCRIPTION OF THE FIGURES

The invention is further described with reference to the accompanying figures in which:

Figure 1 illustrates indicative scatterers in an outdoor multipath environment,

Figure 2 illustrates the effective scatterers with a "past" trajectory over which the scatterers are characterised and a "future" trajectory over which the channel can be predicted from the channel model,

Figure 3 shows a configuration for applying the method of the invention to diversity channel (antenna diversity) combination,

Figure 4 shows a configuration for applying the signal prediction method of the invention to equaliser control and/or rake control,

Figure 5 shows a configuration for applying the signal prediction method of the invention to signal detection and/or decoding, and

Figures 6(a) and 6(b) are plots of predicted channel amplitude and phase referred to further in the example below.

DETAILED DESCRIPTION

In the method of the invention first past samples of the channel behaviour are obtained from samples of the signal originally received by the antenna. It may be necessary to avoid "corruption" of the samples of the radio channel by compensation or correction of any "unwanted" changes in the transmitted signal (through amplitude or phase modulation). Such changes may in turn corrupt the prediction process. The avoidance can be achieved by known techniques such as using an appropriate signal modulation, or adding a component to the transmitted information signal for "sounding" the channel, such as a pilot carrier or a signature signal in a repeating time slot of the transmission.

The past samples are then processed to characterise the multipath components, or an equivalent set thereof, of the signal received by the antenna. This requires

computation typically by a digital signal processor. In a changing radio channel, the past samples are continually updated, resulting in the estimate of the future behaviour being continually updated.

The estimated multipath signal characteristics are then used to estimate the future behaviour of the radio channel, based on the assumption that the future mobile trajectory is known. The calculation is again typically interpreted in a digital signal processor. The future trajectory of the mobile is assumed to be following the same trajectory, as when the prior samples of the channel were taken, although the patent is not restricted to this.

The knowledge of the future radio channel behaviour is then applied to process signals, or to control or to help control a process, in order to improve the channel quality. Diversity signals from diversity antenna branches, or from diverse frequency channels, or from other diversity channels such as rake channels, can be combined. The effect of the changing phase and/or amplitude of the received signals can be effectively corrected before and during the signal detection stage. The knowledge of the future radio channel can be used to control antenna diversity, equalisers and rake processors, or other processors to mitigate multipath effects.

Model and Prediction Technique: The model for the short-term channel behaviour feature the Rayleigh-like fading of the envelope comprises a set of effective scatterers whose discrete contributions are summed. The model is written in terms of the baseband equivalent transfer function which depends on position z and baseband frequency ω

$$h(z_9\omega) = \sum_{i=1}^{n} a_i e^{ju_i z} e^{-j\omega\tau_i} \qquad (1)$$

The effective scatterers are constant over a neighbourhood of the receiver position. They are characterised by their number, N, complex amplitudes, a_i,

their directions given by the spatial Doppler frequencies, $u_i=k_c\cos\theta_i$, and delay times, T_i. k_c is the wavenumber of the carrier frequency. The size of the neighbourhood in space and frequency over which the effective scatterers are constant is not known from a snapshot receiver signal, but if the physical scatterers are in the far-field of a lineal locus of the mobile then for narrow relative bandwidths, the effective scatterers will be constant for at least a few wavelengths at microwave frequencies. In dealing with effective scatterers, recall the effect of the antenna is included.

The scattering model, with known static scatterers, gives the possibility of knowing the channel transfer function (in the neighbourhood) before the mobile has reached that position. How this can be done is demonstrated by addressing only the narrowband (ie flat-fading) channel, ie:

$$h(z) = \sum_{i=1}^{n} a_i e^{ju_1 z} \qquad (2)$$

The re-inclusion of frequency does not alter the prediction concept. The invention also includes the prediction of frequency-behaviour in an analogous way to distance behaviour. The frequency prediction is useful in wideband systems such as the IMT-2000 type mobile communications systems.

Firstly the scatterers must be characterised. Then scatterers can be tracked, in principle, since they are slowly changing with respect to the mobile position. The concept is illustrated in Figures 2(a) and (b). During the interval of channel characterisation, the prediction covers the interpolation of the channel behaviour between the sampled positions (or sampled frequencies, or both).

Ideally, the samples are uncorrelated, but the samples will normally have non-zero correlations, and any solution algorithm should be sufficiently robust to handle this. The samples can be written as

$$h_1 = h(z_1) = a_1 e^{ju_2 z_1} + a_2 e^{ju_2 z_1} \ldots + a_N e^{ju_N z_1}$$

$$h_2 = h(z_2) = a_1 e^{ju_2 z_2} + a_2 e^{ju_2 z_2} \ldots + a_N e^{ju_N z_1} \tag{3}$$

$$h_M = h(z_M) = a_1 e^{ju_2 z_M} + a_2 e^{ju_2 z_M} \ldots + a_N e^{ju_N z_M}$$

in which M complex samples are taken to characterise N effective scatterers. There are 3N real unknowns (each of the u_i, $Re\{a_i\}$ and $Im\{a_i\}$) and for each equation there are two real knowns ($Re\{h_i\}$, $Im\{h_i\}$). The number of independent equations required for solution is $M \geq 3N/2$. If the samples are truly uncorrelated, then $M=3N/2$ is sufficient. For correlated samples, more sophisticated methods are required which produce a solution which is optimal in some sense (see below).

In {1}, samples of the various *h(x)* are taken at various *h(z)*. In {2}, a system of non-linear simultaneous equations (1) is set up and this set is solved to give the various a_i and u_i. In {3}, the future behaviour at the various future positions z_j, is calculated from applying (1) with z_f. This z_f becomes the z_j as z progresses, and the calculation updates continually with new z_f and z_j.

In the first method a large number (cf., N in equation 1) of parameters (cf., the complex a_i and the u_i) are found which characterise the channel. The parameters are found using the above simultaneous equations approach or found (estimated in some optimal sense) via known signal processing techniques such as the many methods established for spectral analysis [see for example, S.M.Kay and S.L.Marple, "Spectrum Analysis, a Modern Perspective", *Proceedings of the IEEE*, Volume 69, pp. 1380-1419, November 1981; and Kay: *Modern Spectrum Estimation*, Prentice-Hall, 1987]. The advantage of solving for many parameters is

that the interpolation and extrapolation can be very accurate and the extrapolation can extend to cover many fades. The disadvantage is that this takes considerable computing power and time which is a problem for power efficient terminals such as personal communications devices.

In the second method, a greatly reduced number of parameters are found which are "good enough" for channel prediction over a shorter prediction interval. For example N may be as low as 2 to 5. This has the advantage of offering feasible implementation using low power processing such as available in small personal terminals. The feasibility is based on the fact that relatively low processing power (processing capability) and quick estimation can be achieved for low battery power consumption.

The estimates of the a_i and the u_i is a critical part of the process. The application of the signal processing techniques which track and predict changes in the a_i and the u_i (cf Kalman-type filters) will clearly assist or improve {3} and therefore the performance of breadth of applications.

The invention includes the case where h is multidimensional, and in particular the two-dimensional case where h is a function of z and frequency ω. The variation in $h(z,\omega)$ over a frequency band is then sampled {1} in both z and ω and the solution process (2) gives $a(\tau, u)$, where τ is the set of relative time delays of each contribution a_i is the direction u_i. Samples of the magnitude only of $h(u,\omega)$ are sufficient, in principle; since it is known that, in principle, the complex $h(u,\omega)$ can be calculated from the magnitude of $a(\tau, u)$. This means,. in particular,, that constant envelope modulation can be used, and the complex channel can be derived without the need for a pilot type signal.

The application of the invention may be in current and in particular in future communications systems where the rate of change of the channel is relatively fast. An example of such a system is an IMT-2000 - type mobile communications system which must be able to operate with fast fading channels when the mobile

terminal is moving quickly (up to 500 km/hr) and microwave frequencies (1.8/1.9 GHz) are employed.

Figure 3 shows a configuration for applying the method of the invention to diversity channel (antenna diversity) combination.

Figure 4 shows a configuration for applying the signal prediction method of the invention to equaliser control and/or rake control.

Figure 5 shows a configuration for applying the signal prediction method of the invention to signal detection and/or decoding. In each case the signal processing is standard, but using "feed-forward" setting of the weights.

Reliable amplitude and phase measurements have been performed where the non-line-of-sight channel was sampled every 5 msec at constant mobile speed. The speed of the mobile is not important because the technique employed just assumes constant speed. Method 2 was used with the equations above. Figure 6(a) shows the phase of the channel. The solid line depicts a linear interpolation of the channel measurement samples. The crosses depict the samples of the interpolated channel signals from N=2 parameter set. The circles are the extrapolated (predicted) channel samples. The predicted samples show that the phase was predicted accurately over a distance of about 20 samples and that the samples follow the phase "jump" at sample 12. The prediction in this example begins to become less accurate at sample 25. Figure 6(b) shows the amplitude for the same example. The amplitude of the first two "future" maxima are well defined and accurate to about 1 dB for the first one and about 5 dB for the second one.

This demonstrates the prediction mechanism using real-world signals. This can be used in known signal processing techniques for improving the channel. Using method 2 allows simple signal processing to be deployed and few-finger rake receivers and the use of switched antenna diversity are obvious applications.

The foregoing describes the invention including preferred forms thereof. Alterations and modifications as will be obvious to those skilled in the art are intended to be incorporated within the scope hereof, as defined in the accompanying claims.

CLAIMS

1. A method for predicting future channel behaviour for a multipath time-varying channel, in a communications receiver including an antenna, comprising:

(a) obtaining samples of the past channel behaviour from the received signal;

(b) processing the past samples to characterise the multipath components, or an equivalent set thereof, of the received signal;

(c) estimating the future channel behaviour from the estimated multipath signal characteristics; and

(d) applying the channel behaviour prediction information in the processing of signal subsequently received to improve the channel quality.

2. A method according to claim 1 wherein the antenna is moving and the future mobile trajectory is predicted from the received signal, data gathered from other sensors, or from prior knowledge or assumption of the mobile trajectory.

3. A method according to claim 1 or claim 2 wherein the channel behaviour prediction information is used in combining diversity signals from diversity antenna branches or from diverse frequency channels or from other diversity channels including rake channels, and/or to effectively correct the phase and/or amplitude of the received signals before or during the signal detection stage.

4. A method according to claim 1 or claim 2 wherein the channel behaviour prediction information is used in the control of an equaliser or rake processor or other processor in the receiver arranged to mitigate multipath effects.

5. A method according to any one of claims 1 to 4 wherein said characteristics comprise the direction, amplitude, and phase of the principle multiple signals received by the antenna.

6. A communications receiver including an antenna, including:

(a) means arranged to obtain samples of the past channel behaviour from the received signal;

(b) means arranged to process the past samples to characterise the multipath components, or an equivalent set thereof, of the received signal;

(c) means arranged to estimate the future channel behaviour from the estimated multipath signal characteristics; and

(d) means arranged to apply the channel behaviour prediction information in the processing of signal subsequently received to improve the channel quality.

7. A communications receiver according to claim 6 wherein the channel behaviour prediction information is used in combining diversity signals from diversity antenna branches or from diverse frequency channels or from other diversity channels including rake channels, and/or to effectively correct the phase and/or amplitude of the received signals before or during the signal detection stage.

8. A communications receiver according to claim 6 or claim 7 wherein the channel behaviour prediction information is used in the control of an equaliser or rake processor or other processor in the receiver arranged to mitigate multipath effects.

9. A communications receiver according to any one of claims 6 to 8 wherein said characteristics comprise the direction, amplitude, and phase of the principle multiple signals received by the antenna.

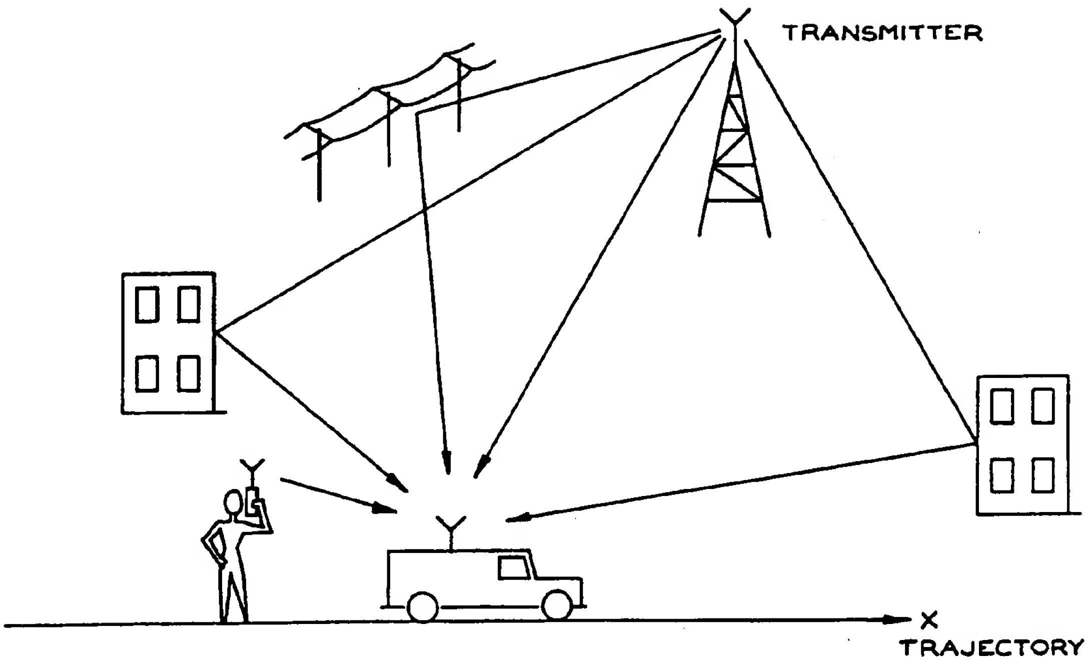


Figure 1

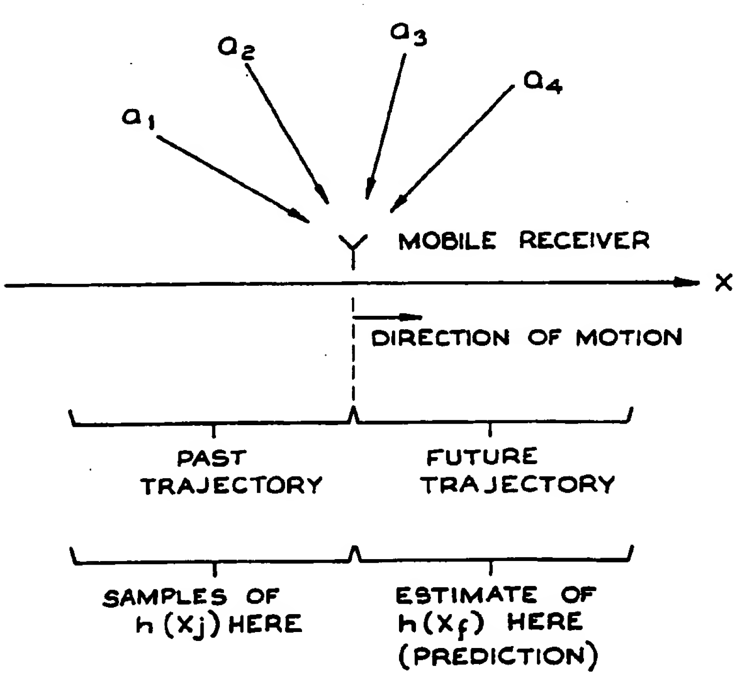


Figure 2

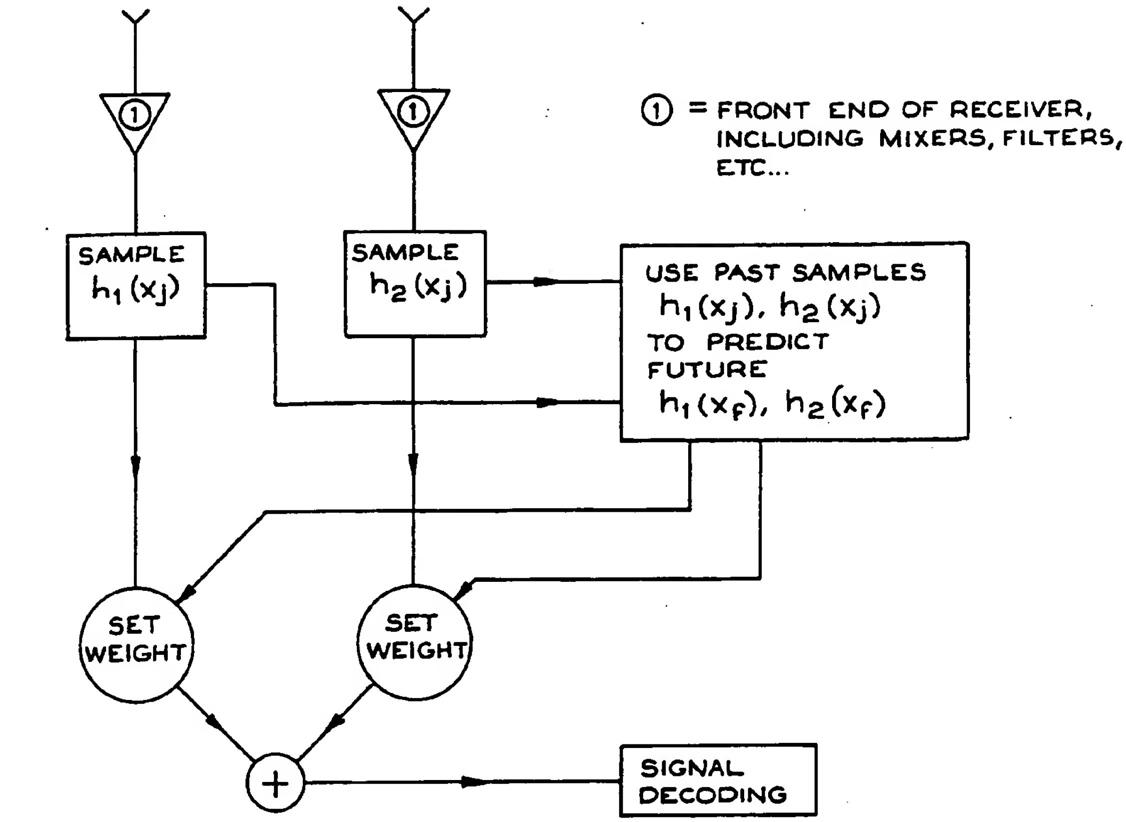


Figure 3

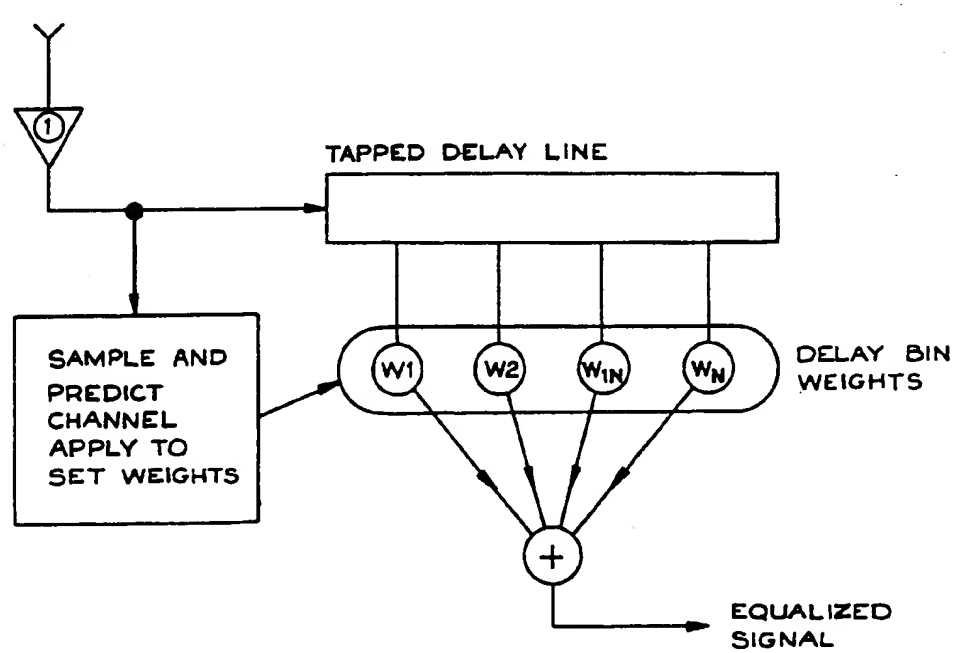


Figure 4

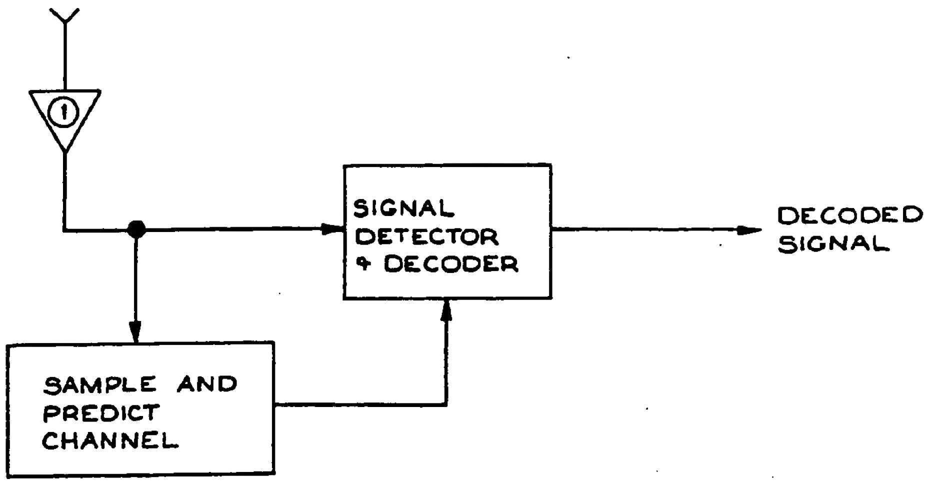

SIGNAL
DETECTOR
& DECODER
DECODED
SIGNAL
SAMPLE AND
PREDICT
CHANNEL

Figure 5

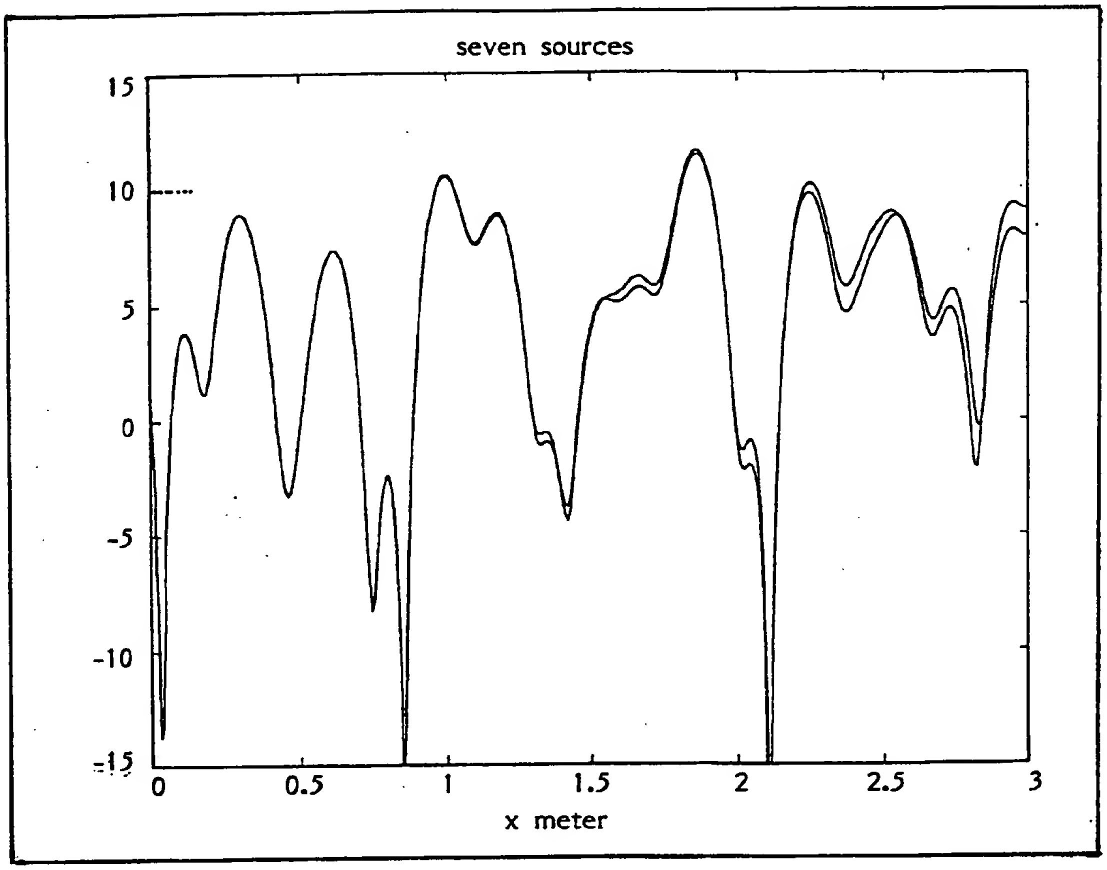


Figure 6